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Innovative Composite Structure Design for Blast Protection

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ABSTRACT

An advanced design methodology is developed for innovative composite structure concepts which can be used in the Army's future ground vehicle systems to protect vehicle and occupants against various explosives. The multi-level and multi-scenario blast simulation and design system integrates three major technologies: a newly developed landmine-soil-composite interaction model; an advanced design methodology, called Function-Oriented Material Design (FOMD); and a novel patent-pending composite material concept, called BTR (Biomimetic Tendon-Reinforced) material. Example results include numerical simulation of a BTR composite under a blast event. The developed blast simulation and design system will enable the prediction, design, and prototyping of blast-protective composite structures for a wide range of damage scenarios in various blast events.

INTRODUCTION

Existent numerical models used for blast simulation can be roughly divided into two groups: the empirical model for blast pressure approximation and the numerical model based on the Lagrange/Euler method. For the empirical blast pressure model, the CONWEP air blast function was developed [1] for blast overpressure determination under certain conditions: the free air detonation of a spherical charge and the surface detonation of a hemispherical charge. While the surface detonation approaches the conditions of a mine blast, anti-vehicular mines are most commonly buried anywhere from 5 to 20 cm below the surface of the soil (sometimes more if a road is resurfaced for example). The depth of burial, among other things, has a significant effect on the energy directed on the target by funneling the force of the blast upwards. Other variables such as soil moisture content and soil type have equally important effects on the mine. However, none of these effects are included in the CONWEP blast model. At the cost of accuracy, the CONWEP method is computationally less expensive than the coupled fluid/structure method.

In a numerical model of a continuum, the material is discretized into finite sections, over which the conservation and constitutive equations are solved. The scheme of spatial discretization leads to different numerical methods. For blast impact simulation, the complexity of the problem lies in the following difficulties: the high speed wave front propagation, the flow of various materials, and the large structural deformation. To our knowledge, the most appropriate numerical method might be the Arbitrary Lagrangian-Eulerian (ALE) method. The ALE solver allows for a type of "automatic remapping" in simulation. The edge nodes of a finite section can be completely Lagrangian (the nodes move with the material motion), while the inner nodes can be remapped so that the mesh is more smooth than the one in the single Lagrangian method. The ALE solver is well suited for a variety of fluid-structure interaction problems. Multiple material ALE can be formulated in a fashion which allows material to flow from cell to cell.

The concept of ALE has been integrated into commercial code such as LS-DYNA3D and CTH. In the Army Research Laboratory, Kerley [2] and Gupta [3] have used the CTH to simulate the buried mine explosion on a receptor (steel plate) with the consideration of soil effect. The CTH code is tuned to minimize the dispersion present in conventional Eulerian methods. Since the mine blast is a hypervelocity impact, the initial momentum determination on receptors can be assumed independent of the elastic/plastic deformation of the composite/metal receptor (Hanssen *et al*. [4] found that soft panel can amplify the blast result, though the amplification is small for rigid panels.).

One drawback for the CTH model in blast simulation is that the soil model must be assumed continuous to carry

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out the simulation. Some results in the Army reports by Kerley [2] and Gupta [3] show that the soil model is inhomogeneous, therefore the CTH code is not appropriate for numerical simulation. Furthermore, the CTH code is time consuming in simulation, which makes the statistical analysis of blast impact effect formidable due to various soil models.

Blast energy is released within a very short period of time (the duration of blast can be less than 1.0 ms), making it hard for protection material to absorb a majority of the blast energy. In order to protect the crew members inside the vehicle and the integrity of the main structure, protection panels are inserted in military vehicles to deflect blast waves [5]. Numerical simulations have been carried out to determine the dynamic loads produced by the mine detonation on the cargo bed and other structural elements of the truck [6]. A series of calculations are designed to simulate the corresponding field tests in which explosive charges of various sizes were detonated beneath instrumented vehicles. Using numerical analysis, a wedge/wing deflector structure was designed and placed under the truck's cab [5].

The successfully developed crew/vehicle protection panel can increase crew survivability of tactical wheeled vehicles subject to mine blasts. However, these protection kits are based on conventional steel/aluminum construction, and are close to 0.5 ton in weight. A sandwich structure has been proposed and tested for an alternative design [7]. Experiments have been carried out to test the composite panel under blast, which found the panel cannot restrain the maximum deflection as well as the original alloy panel [7]. Due to the deficiency in inter-laminar strength of the sandwich panel's faces and the subsequent consequence from dynamic blast loading, the dynamic deflection of the panel is not satisfactory compared to the past monolithic panel test results. A new material model [8] has been developed and integrated into the commercial FEM code, LS-DYNA, to account for progressive failure mode of composite panel. Some guidelines for composite panel design for blast protection have been summarized [8].

Protecting buildings from explosives is a closely related topic of blast protection. Extensive research has been conducted in this field for advanced protective building structure designs. Innovative concepts developed for protecting the buildings can be learned from new structural concepts for protecting vehicle and crew. Crawford [9] summarizes some interesting ideas developed in civil engineering for building protection, including i) a cable-reinforced window concept, where the glass fragmentation under a blast attack has been prevented by installing reinforcing cables in the window; ii) a bi-plate concept of a building structure, which can be used to make, for example, a roof, for better protection; iii) a multi-layered composite concept for a wall design against blast, which includes three different layers, from outside to inside: 1) bricks, 2) polyurethane foam core bonded to bricks with adhesive, and 3) metal or FRP (Fiber Reinforced Polymer) skin used to catch wall debris. These innovative ideas can be useful when considering a blast-protective composite structure design for vehicle systems.

In blast protection, foam and fiber materials are widely used. Aluminum foam is a lightweight material with excellent plastic energy absorption capability. The characteristics of aluminum foam in close-range blast loading have been investigated [4], including field tests and simple analytical simulations. The use of foam material as blast energy absorption has the following advantages: i) increase the captured energy to receptors; ii) reduce the force/stress transmitted to main structure; iii) achieve protection of main structure.

Fiber-reinforced composites can also be tailored towards high energy absorption [10]. Impact-damaged composite panels constructed using glass fibers that adhere poorly to the polymer matrix display large damage areas due to extensive fiber-matrix debonding, pullout, and delamination mechanism. The major difficulty in energy-absorption fiber-reinforce composite design is in obtaining reasonable structural properties as the traditional (well bonded) composite. Some achievements [10] have been made through unique chemistry processes in the fiber-matrix interface. The achievement of excellent structural properties has been obtained with concurrent superior impact energy absorption characteristics. The study shows strong rate dependence before, during, and after fiber-matrix debonding; and the post-debonding frictional mechanism is found to absorb a great amount of energy.

This paper is organized as follows: Blast model is discussed first, followed by numerical examples based on LS-DYNA3D. A design methodology is then introduced for blast protection with an example of optimal composite plate design. Finally, a composite material concept for blast protection is discussed.

DEVELOPMENT OF A NEW LANDMINE-SOIL-COMPOSITE INTERACTION MODEL

Prediction of blast load on the composite structure is the first step for designing an advanced blast-protective composite structure. Many blast models and computational methods have been developed in the past with a focus on predicting blast overpressure on the structure surface. Details of soil behaviors are ignored and only average behavior is considered. However, the detailed texture and composition of soils may have significant influence on the simulation fidelity of the explosion process as well as on the damage prediction of the composite structure [3]. At this stage, there is no efficient method which can predict both blast overpressure and the fragments that penetrate the composite structure, even though fragments may cause more serious damages to the vehicle structures and crew members.

NEW BLAST LOAD MODEL

A numerical simulation scheme is developed to more accurately predict landmine-soil-composite interactions. In this model, the soil is discretized into small segments with detailed consideration of soil structure and texture (e.g., density, porosity, and failure criteria). As shown in the example in Fig. 1, a buried mine is represented by JWL equation of state. The top soil is then discretized using a statistical scheme that can represent soil structure and texture in a statistical way based on experimental data. The base soil is still assumed to be a continuum and is modeled as the conventional soil model (e.g., using Hugoniot curve [3]). An air blast model is further developed to model the blast air, which interacts with the debris and contribute to the overall pressure/impact force on the composite structure. Using this discretization scheme, the inhomogeneous property of soil, and interactions between the blast wave and soil debris; the true loading condition of the composite structure can be accounted for in the blast load prediction.

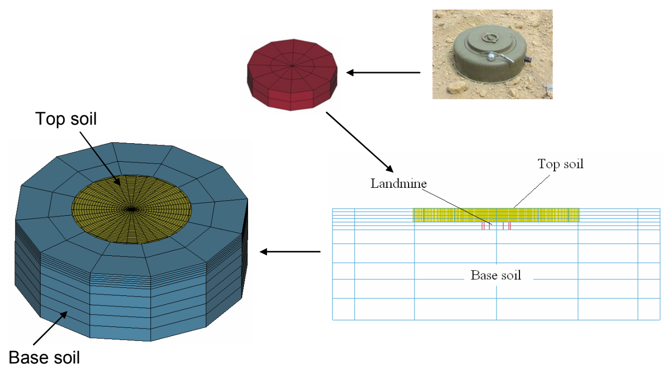
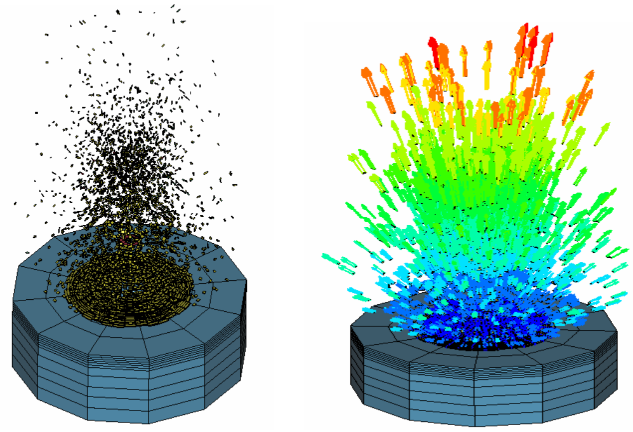


Figure 1. The simulation scheme for mine-soil problem

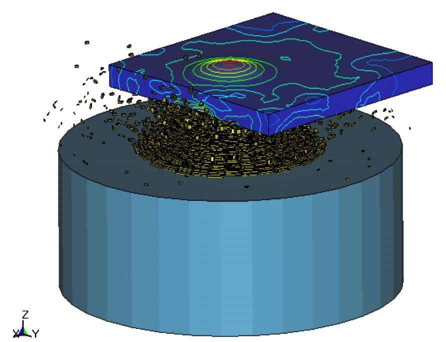
The example in Fig. 2 illustrates preliminary simulation results obtained using the proposed landmine-soil-composite interaction model (LS-DYNA3D is used for numerical simulation). As shown in Fig. 2-a, a real soil ejection under a landmine explosion can be simulated using the proposed simulation model, where velocity (and therefore momentum) of individual soil debris can also be predicted as shown in Fig. 2-b.

Figure 3 illustrates the soil debris-structure interaction when a steel plate is placed to capture the soil debris as well as the blast wave (LS-DYNA3D is used for simulation). It is seen that the whole landmine-soil-structure interaction process can be simulated with both effects of blast wave and soil debris. This simulation capability will be further benchmarked to compare with available experimental results and other valid simulation models.

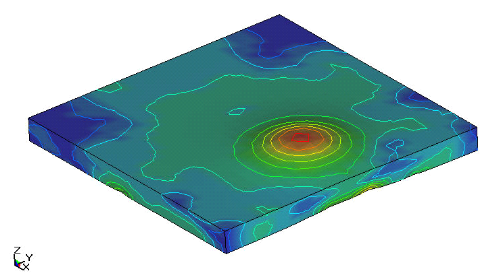


(a) Top soil explosion (b) Explosion velocity

Figure 2. Landmine-soil blast simulation using the proposed simulation model



(a) Soil debris-structure interaction



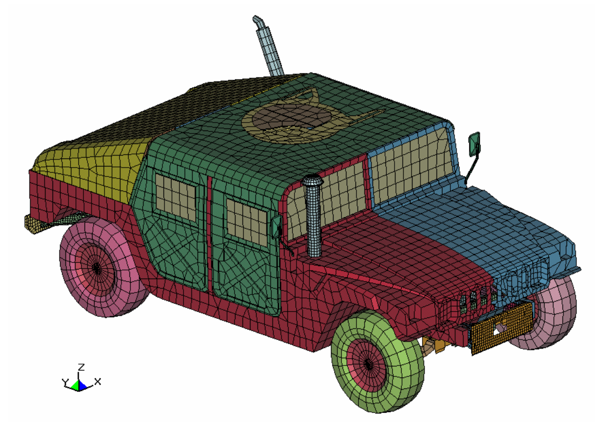
(b) Resultant stress inside the plate

Figure 3. Landmine-soil-structure blast simulation using the proposed simulation model

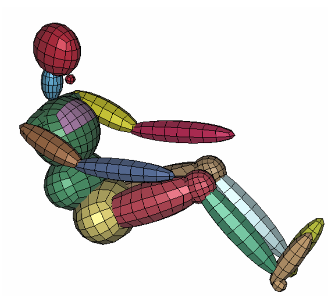
PREDICT DYNAMIC BLAST LOADS ON VEHICLE

A HMMWV model (shown in Fig. 4-a) has been developed and a dummy model (shown in Fig. 4-b) has been found in the public domain from LS-DYNA3D, which can be used to further examine effects of

landmine-soil-structure interaction at the vehicle level and on the crew members. Preliminary simulations have been conducted in the LS-DYNA3D environment, and results are illustrated in the following subsections.



(a) HMMWV model with 30,746 finite elements



(b) Dummy model (from LS-DYNA3D)

Figure 4. HMMWV and dummy models for blast simulations

Effects of blast loads on the vehicle

Figure 5 shows a snapshot of the damage and deformation simulation for a HMMWV under a mine attack. The landmine is detonated under the driver seat. As illustrated, the floor under the seat has been significantly damaged. The resultant acceleration on the dummy can also been predicted. As in this case, the dummy will be seriously injured if no additional protection is provided. The model shown in Fig. 5 will be further investigated to provide realistic predictions for the landmine-soil-vehicle interactions so that it can be used for advanced protective composite design.

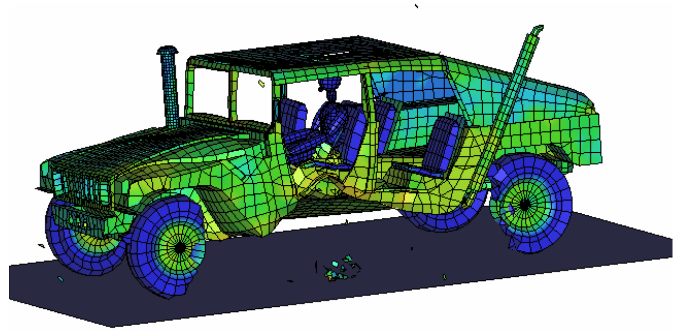
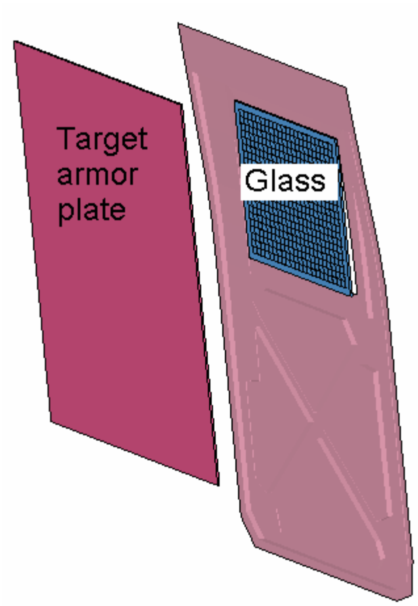


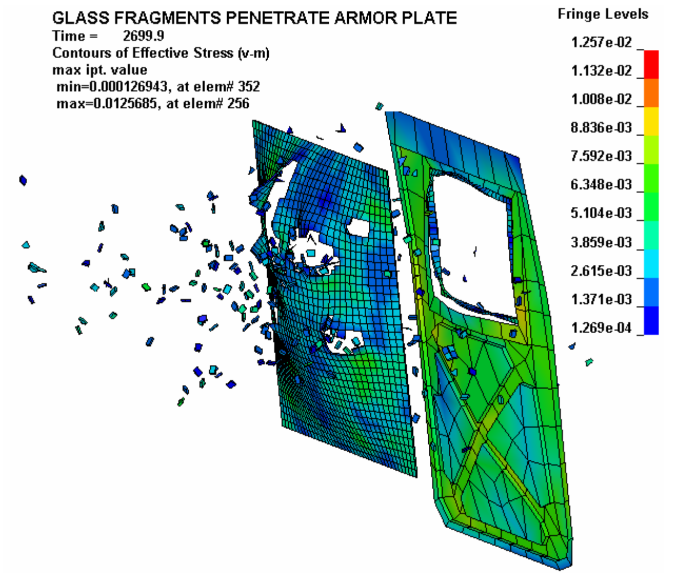
Figure 5. Example result of landmine-HMMWV-Dummy blast simulation

Effects of blast load on a vehicle substructure – driver's side door

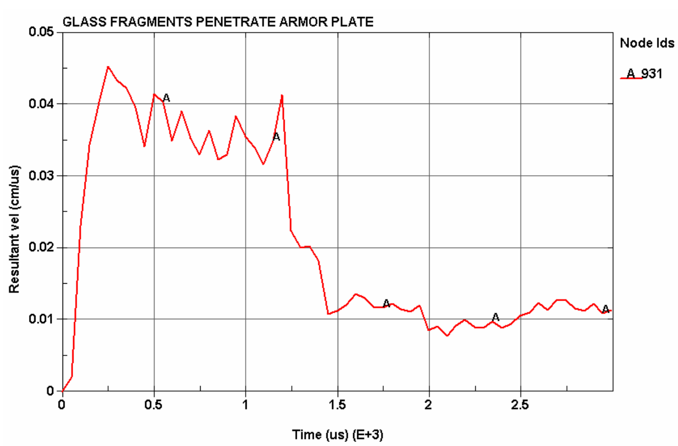
Blown-out glass from vehicle windows can generate a large number of fragments, which may fatally injure the occupants. Fragments can also be generated when, for example, landmines are detonated under tires or other structures. Large pieces of the tire or other parts of the wheel or brakes can penetrate the floor and fatally injure occupants. In addition to the blast pressure, it is important to predict the fragmentation and potential effects on the vehicle structure. This information can be used as a target when designing a protective structure and to evaluate the performance of the protective structure designed. Figure 6 illustrates that the fragment penetration damage on an example armor structure (Fig. 6-a) can be simulated using the capability developed, and the velocity of each individual fragment (Fig. 6-b, c) can be predicted, which can be used for the advanced composite armor design.



(a) Configuration of armor and glass



(b) Fragment penetration process



(c) Velocity history of a fragment

Figure 6. Fragments from window glass penetrate an armor plate

OPTIMAL COMPOSITE STRUCTURE DESIGN FOR BLAST PROTECTION

Current composite armor design processes rely heavily on testing, which can be expensive and time-consuming. To expedite the development of composite armor design, a combined design process is proposed with a core design methodology developed at MKP Inc. This design methodology is called *Functional-Oriented Material Design* (FOMD), which was developed under two US Army and US Air Force SBIR Phase II programs, and has proven to be an effective tool for innovative structural and material designs for needed light-weight and high-performance [11]. It will be used to design materials and structural components for the specific tasks demanded in future ground and air vehicle systems. In order to carry out the FOMD process, the functions of a structure in the vehicle system need to be explicitly defined in a systematic way. Then these functions must be quantified, so as to define the objective and constraint functions in the optimization process. Finally, an advanced optimization process needs to be carried out, and the material layout has to be finalized by the design engineer. Typically a number of constraints, such as manufacturing and cost, need to be considered in the optimal design process. Note that the term “material design” used here can take two different meanings, micro-structural design and macro-structural design.

Figure 7 illustrates the proposed simulation and design process for developing the advanced composite concept for blast protection. This design process includes: i) explosive modeling; ii) soil modeling; iii) geometry modeling of vehicle structure and occupants; iv) blast prediction, which will predict both blast pressure and fragment penetrations on the composite; v) composite layout, which includes raw material selection and material configuration, and vi) optimal design based on FOMD and topology optimization. A post-process will also be conducted to finalize the design for prototype manufacturing.

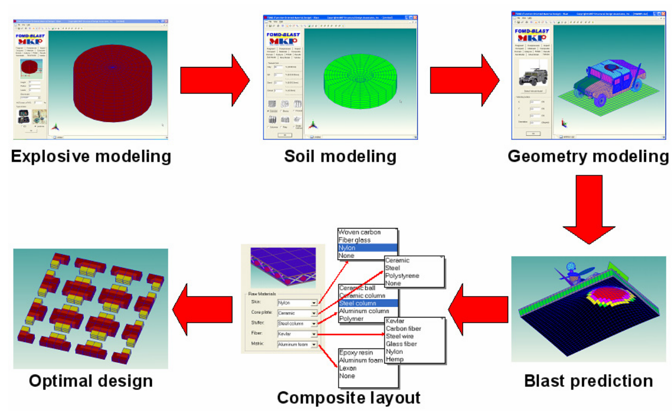


Figure 7. Proposed simulation and design process

Figure 8 illustrates a preliminary study using the current FOMD-Blast for a special sandwich composite design under a landmine explosion. Only blast pressure is considered in this design case. Effects of the blast-soil interaction and fragmentation are ignored. The composite plate is assumed to have dimensions of 2.44 m x 2.44 m, and the landmine is detonated at 0.61 m beneath the composite plate with a specified charge. The sandwich is assumed to have three layers: the top layer is made of aluminum and the bottom layer is made of steel. The design problem is to lay out the optimum reinforcing material distribution in between the aluminum and steel plates with a given amount (mass) of material so that the strain energy stored in the sandwich due to the blast can be minimized. As an initial study, the optimum design is considered with respect to the blast loads at different moments of the explosion, which are 0.03 ms, 0.15 ms, and 0.3 ms. Because the blast load

distribution varies with time, as shown in the top row of Fig. 8, different optimum reinforcement designs are obtained, which are shown in the middle row of Fig. 8. The bottom row of Fig. 8 further illustrates the von Mises stress distribution in the optimum composite structures under the corresponding blast loads. Note that the final design should be obtained in consideration of either the most critical loading case or multiple loading conditions, which can represent the overall blast damaging process. This will be studied in the future.

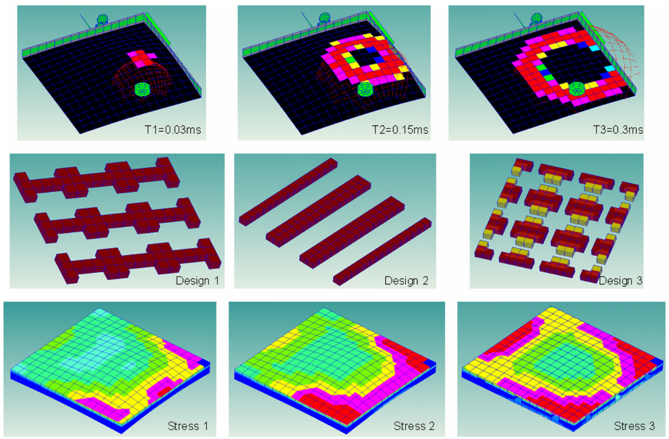


Figure 8. Proposed simulation and design process example results for reinforcing stuffer design under blast loads at different time (The optimum design will consider all possible worst cases.)

NEW BLAST-PROTECTIVE COMPOSITE CONCEPT (BTR-*BL*)

The present armor concept to defeat light to medium threats typically consists of a hard and strong frontal surface and a relatively softer backing structure with specified toughness and strength. In addition to ballistic and blast protection, other major requirements for advanced vehicle armor are lightweight, flexibility, maintainability and reduced life-cycle cost. Lightweight is crucial to maintaining excellent road and cross-country mobility, which is directly related to military deployability and survivability. Lightweight is also crucial to the transportability and sustainability as well as to structural integrity and durability. Flexibility means the armor structure can be shaped or formed to fit various vehicle contours. Maintainability implies two things: i) the integrated armor system can be easily installed and removed from the vehicle with minimal time and manpower, and ii) the armor can be easily repaired during war time without replacing the whole armor structure. Life-cycle cost is directly related to affordability by the US military and the wide application of the armor system.

THE BTR-*BL* COMPOSITE

MKP's blast-protective Biomimic Tendon Reinforced (BTR-*Bl*) material concept is used to build an under-body deflector. Figure 9 illustrates a preliminary concept of the blast-protective BTR-*Bl* material, including the following five modules: i) a thin skin layer; ii) a protective layer with energy absorption material; iii) a ceramic plate; iv) a fiber-reinforced composite plate made of cable tendons, stuffers, and foam matrix; and v) woven fiber laminates for inner surface(s).

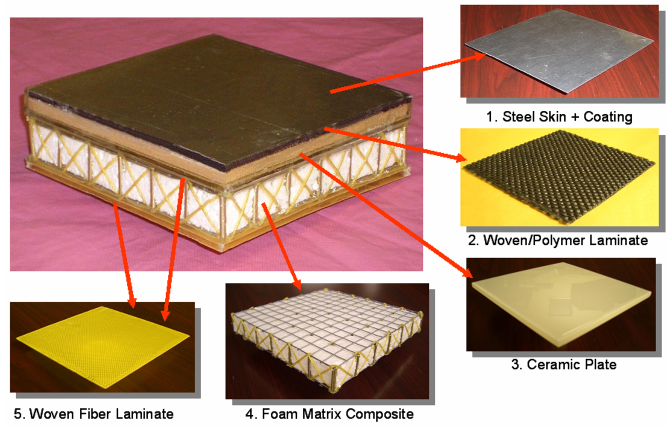


Figure 9. Example configuration of proposed blast-protective composite (BTR-BI) material (MKP patent pending)

Also note that the use of cable in the composite structure has the following advantages:

- Cables can quickly transfer the blast energy to a far-reaching area, thus reducing the localized damage;
- Cables can sustain large-amplitude deformation to capture more blast energy;
- There is a wide ranging selection of high blast toughness materials for cables, such as Kevlar and Nylon, which can be used to develop super-tough composite for blast protection.

Cable reinforcements will work well with other materials in the system, such as with foam matrix as a tough energy absorption material.

BLAST LOAD ON BTR COMPOSITE STRUCTURE

Figure 10 illustrates the numerically investigated BTR composite under blast load. The BTR composite is composed of s2-glass composites, spherical stuffers, cables, and foam core. Foam material can include aluminum foam, or other high performance synthetic foam, and is integrated into the BTR structure for blast protection improvement. A steel frame is glued to the BTR plate to represent the vehicle frame.

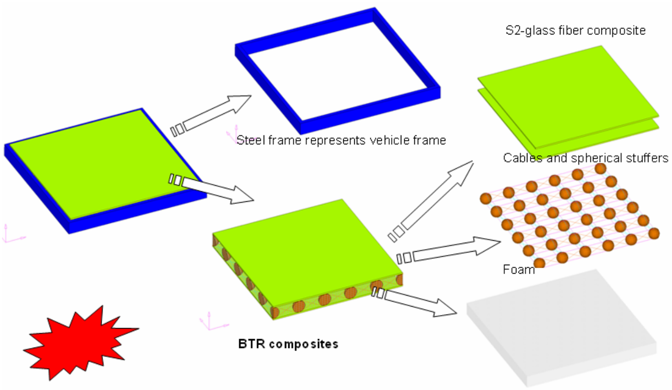
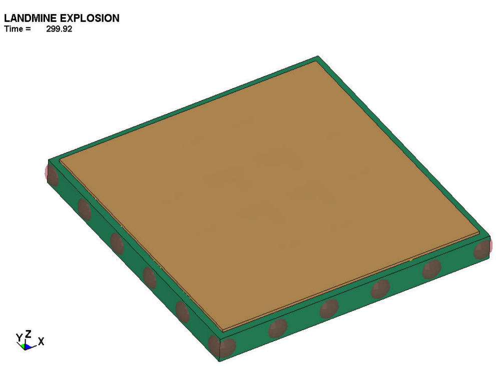
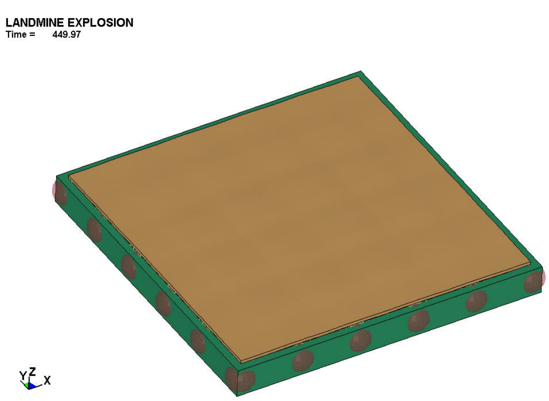


Figure 10. The BTR composite sample

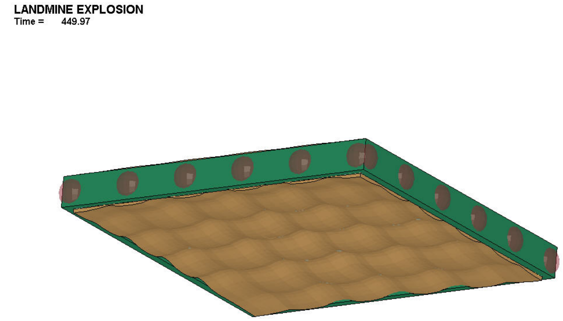
Commercial FEM code LS-DYNA3D was used for this simulation. The BTR composite deformation is recorded in Fig. 11 at individual time steps until the composite damaged. During the blast, the bottom surface had localized deformation at the early stages of the blast (Fig. 11-a and b). After 0.45 ms, the bottom surface will have global deformation (Fig. 11-c). The blast load will then be transferred to the top surface (see Fig. 11-d, e, and f). The inner cable and bead deformation is plotted in Fig. 12 at the final blast stage (5.8 ms) for the BTR composite. The cables have significant deformations while the beads are almost intact due to their high compressive strength.



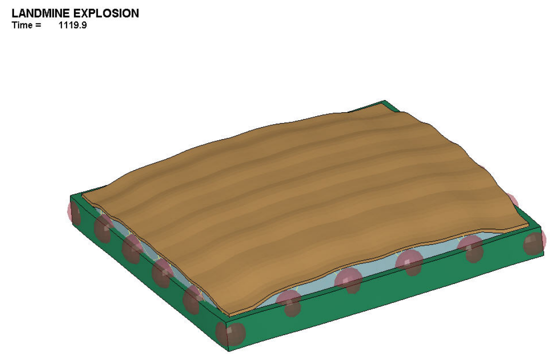
(a) time = 0.3 ms, top surface



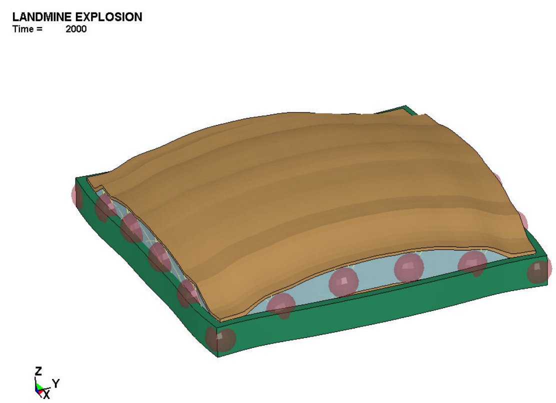
(b) time = 0.45 ms, top surface



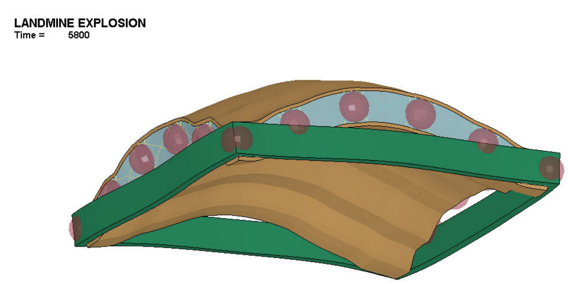
(c) time = 0.45 ms, bottom surface



(d) time = 1.12 ms, top surface



(e) time = 2.0 ms, top surface



(f) time = 5.8ms

Figure 11. Deformation of BTR composite with foam core at discrete time events

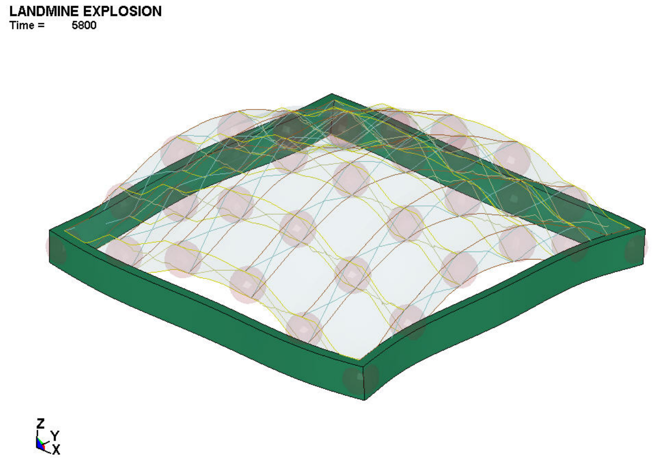


Figure 12. The inner foam, cable, and bead deformation of the BTR composite with the foam core under blast load (time = 5.8 ms)

The momentum transmitted to the BTR structure is compared in Fig. 13 for two different BTR structures, one with foam core (the deformation is shown in Fig. 11 and 12) and one without. The BTR composite without foam core failed at 2.2 ms while the momentum transmission was much slower for the BTR composite with foam. Consequently, the composite structure with foam can undergo much larger deformation under the same blast load. The BTR composite with foam can delay the composite damage time (5.8 ms) compared to the damage time of the composite without foam core (2.2 ms). The foam material undergoes large deformation and absorbs energy. As a result, the force transferred to the main structure can be reduced.

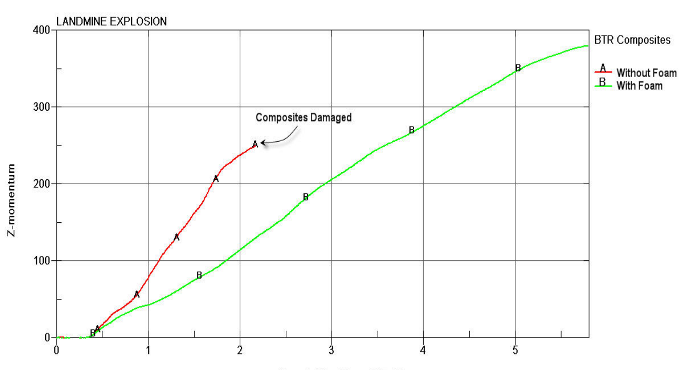


Figure 13. Comparison of the momentum transmitted to the frame structure: red line denotes BTR composite without foam core; green line for the BTR composite with foam core.

CONCLUSION

The developed blast simulation model and optimal design system will enable the prediction, design, and prototyping of blast-protective composite structures for a wide range of damage scenarios in various blast events, ranging from vehicle damage, localized structural failure, blast fragment penetration, to crew injuries. From the study of the proposed BTR composite, the BTR composite can help the structures to sustain blast load. The inclusion of foam material in BTR composites can absorb energy under blast load and help to reduce the force transmitted to the main structure. Furthermore, foam material helps to reduce stress concentration in BTR composites. Consequently, the BTR composite structure can undergo larger deformation without severe damage. In the future, different levels of simulation and design capabilities will be implemented in an integrated software system called FOMD-Blast with a well-defined graphic user interface.

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